F. Crash Analysis of Adhesively Bonded Structures (CAABS)

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Objectives

- Develop a comprehensive experimental and analytical methodology to analyze and design adhesively bonded automotive composite structures to sustain axial, off-axis, and lateral crash/impact loads.
- Determine the rate sensitivity of bonded tubes to crush through experiments on the Oak Ridge National Laboratory (ORNL) Test Machine for Automotive Crashworthiness (TMAC).
- Determine influence of critical joint design parameters, for example, bond length, bond thickness, and fillet, on specific energy absorption.
- Experimentally determine the full-field deformations at joint discontinuities for validation of analytical/numerical results.

Approach

- Coordinate with the bonded joint experimental and analytical efforts undertaken in the Automotive Composites Consortium (ACC) project “Composite Crash Energy Management.”
- Select a substrate, adhesive, and representative subcomponent joint geometry for evaluation.
- Characterize substrate material, adhesive material, and coupon level joints under static and dynamic loads.
- Build and test unbonded and bonded rail components under static and dynamic crush loads.

- Correlate experimental results with analytical results by developing finite-element-based tools with appropriate material models and progressive damage algorithms.
- Enhance the understanding of joint performance by conducting full-field deformation measurements using moiré interferometry.

Accomplishments

- Fabricated near void-free bulk adhesive panels and cylindrical rods for adhesive characterization studies.
- Characterized tensile and compressive response and fracture toughness of bulk adhesive at quasi-static load rates.
- Characterized static behavior of the braided carbon fiber substrate under uniaxial tension and compression loads.
- Completed preliminary dynamic stability tests on both unbonded and bonded tubes using TMAC.
- Designed and a fabricated a slack adapter for conducting dynamic coupon-level tests.
- Completed preliminary static tests on specimens having single lap joint geometry to determine influence of critical joint design parameters on specific energy absorption.
- Completed limited dynamic tests on the braided carbon fiber substrate and the bulk adhesive.

Future Direction

- Procure new high-rate test apparatus for conducting coupon-level dynamic tests.
- Complete static and dynamic testing of substrate, bulk adhesive, and coupon-level joints.
- Install and set-up moiré interferometric test equipment for characterizing full-field deformation patterns in adhesive joints.

Introduction

The objective of this project is to develop a comprehensive experimental and analytical methodology to analyze and design adhesively bonded automotive composite structures to sustain axial, off-axis, and lateral crash loads. This direct-funded project will be closely aligned with the experimental and analytical efforts undertaken by the Automotive Composites Consortium (ACC) for composite substrates (see 7D of this document). The focus of this work, however, will be restricted to the adhesive joint related issues. The key to the methodology development is the understanding of how critical joint design parameters, for example, bond length, bond thickness, and fillet, affect the energy absorption. Recent investigations at ORNL have provided valuable insight toward the understanding of composite joint performance and composite crashworthiness. The next logical step is determining the correlation between measurable adhesive joint parameters and their influence on the structure to dissipate energy and ultimately predict crashworthiness for a particular composite design.

Experimental tasks include material testing under quasi-static and dynamic loads for substrates, adhesives, and joints; full-field deformation mapping of joints with moiré interferometry for correlation with computational results; strain-rate sensitivity studies; fracture toughness testing; and test method development as required. These experimental results will provide the building blocks for model developments—first at the coupon level, then progressing in complexity to component level. Correlation with experimental results will provide the basis for which the analytical developments, including development of constitutive laws, materials models, damage algorithms, and new finite elements will be made. Structural tests will be conducted on the new intermediate-rate test machine [Test Machine for Automotive Crashworthiness (TMAC)] at ORNL.

Project Deliverables

At the end of this multiyear program, joint parameters that have significant influence on energy dissipation will be identified, and their influence quantified, using appropriate analytical models and experimentation. In collaboration with the ACC Composite Crash Energy Management project, a predictive capability for joint performance will be demonstrated, and the validity of the prediction will be assessed through structural crash testing.

Approach and Results

The technical approach involves both experimental and analytical tasks. There are four main tasks:
Task 1—Materials Selection and Screening,
Task 2—Material Characterization,
Task 3—Component Testing, and
Task 4—Computational Tools Development.

Task 1 was completed and reported on in the FY 2002 annual report. The selected chopped carbon fiber prepreg material system was characterized from flat plaques provided by the vendor. Discussions with the vendor led to an overly optimistic view of the suitability of the material for this project. Additionally, delays in receipt of the material from the supplier resulted in consideration of a carbon fiber sheet molding component (SMC). Both materials are unsatisfactory due to processing difficultly and material variability. As a result of the variability in the initial material screening tests and difficulty in fabricating tubes with this material, the substrate material was changed to a carbon fiber braided system. The woven fabric prepreg is comprised of T300B carbon fiber with a tow size of 3K and 42% (by weight) epoxy resin.

Task 2 was initiated during FY 2002 and was originally scheduled to be completed in the third quarter of FY 2003. The schedule has been adversely impacted by several factors, including delays in substrate material acquisition due to supplier manufacturing constraints and then actually changing the substrate (discussed previously), laboratory-initiated relocation of test facilities from the Y-12 National Nuclear Security Complex to ORNL, operation constraints on TMAC pending pressure vessel certification, and budget constraints. A new schedule is being prepared that takes into account the impact of all these factors.

The substrate will be fully characterized by conducting tension, compression, and in-plane shear tests. The degree of anisotropy in the material will be qualified by testing specimens that are machined from two different orthogonal directions in the panels. This work will be contracted out to an independent testing laboratory by the ACC with a limited set of comparison tests being conducted by ORNL.

Characterization of the tensile and compressive static responses of the substrate material is complete. Tensile and compression testing of specimens that were machined from two different orthogonal directions in the panels indicates similar properties in both directions. Tensile results for five samples, each from two different orthogonal directions in the panels tested at 0.02 mm/s, indicate that average ultimate strength and modulus for the substrate are 70.4 ksi and 5.8 Msi, respectively. Coefficients of variability (COVs) for the strength and modulus results are 3.6% and 1.3%, respectively, which is very good. A typical tensile stress strain curve for this substrate is shown in Figure 1. Compressive results for five samples, each from two different orthogonal directions in the panels tested at 0.02 mm/s, indicate that average ultimate strength and modulus for the substrate are 61.4 ksi and 5.6 Msi, respectively. COVs for the strength and modulus results are 3.9% and 3.2%, respectively. A typical compressive stress strain curve for this substrate is shown in Figure 2. Tests for five substrate samples at 100 mm/s resulted in a decrease in the average ultimate strength to 65.6 ksi, but the average modulus remained the same at 5.9 Msi. COVs for the strength and modulus results

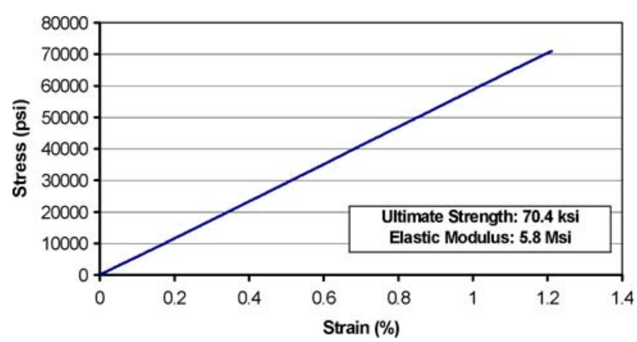

Figure 1. Typical tensile stress-strain curve for the substrate.

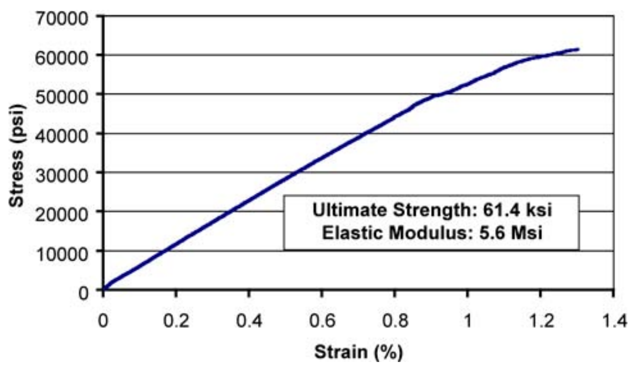

Figure 2. Typical compression stress-strain curve for the substrate.

are 4.3% and 0.8%, respectively, which is also very good.

The adhesive used in this study is an epoxy paste designated as Sovriegn PL731 and is used in many of the research projects within the ACC. The bulk adhesive testing consists of tension, compression, shear, and fracture toughness. In addition, DSC/DMA tests will be conducted to verify the degree of cure. The key to this task is the successful fabrication of high-quality specimens (e.g., low void content) to accurately quantify the bulk adhesive mechanical properties. The compression and shear testing will be accomplished using cylindrical rod specimen geometries. Cylindrical rod specimens were fabricated using centrifugation and glass test tubes as molds. Initial difficulties in producing flat plaques were alleviated by developing a mold-filling process that uses an adequate supply of excess adhesive under pressure to back fill the mold cavity. High-quality specimens for all bulk adhesive tests were fabricated with these two approaches.

Characterization of the tensile and compressive static responses is complete and indicates excellent consistency from specimen to specimen and from plaque to plaque. Tensile results for 18 samples from two different plaques indicate average ultimate strength and modulus for the adhesive are 7.3 ksi and 0.31 Msi, respectively. COVs for the strength and modulus results are 4.8% and 1.6%, respectively, which is excellent. A typical tensile stress strain curve for this adhesive is shown in Figure 3.

Eight cylindrical samples—25-mm long and 12-mm diameter—were subjected to compressive loads (ASTM D695) up to strains of 22% without global failure. Compressive modulus for the adhesive, taken from a range of 1% to 2% strain, is 0.31 Msi, identical to the tensile value. The COV is

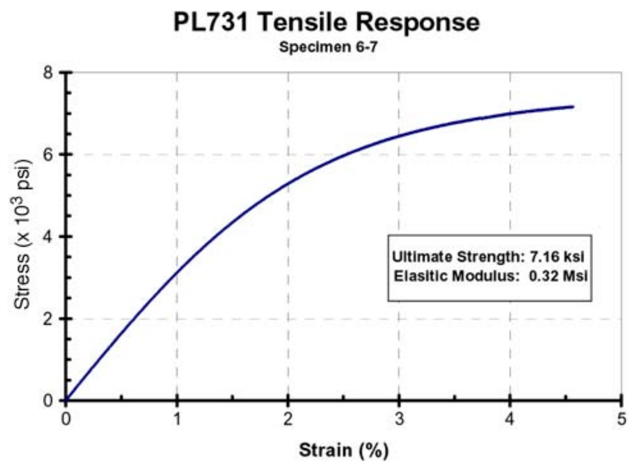

Figure 3. Typical tensile stress-strain curve for the bulk adhesive.

1.6%, consistent with the tensile results. Figure 4 depicts representative "failed" test samples that indicated plastic deformation with small local cracks being present in some samples. Figure 5 illustrates the consistency of the compressive response out to more than 20% strain.

A preliminary shear test for the bulk adhesive was conducted by applying a torsional load to a solid cylindrical rod specimen. The rod was 12 mm in diameter and 100 mm long. Figure 6 shows the measured shear stress-strain response. This specimen did not fail, and the maximum shear strain of almost 13% corresponded to a 60° rotation of the specimen, which was the maximum capability of the test equipment. To achieve a more uniform shear stress distribution and possibly produce an ultimate failure the solid rod specimen geometry was modified to a hollow cylinder. The specimens were manufactured by drilling and reaming the solid rods.

Figure 4. Typical post-test condition of compression samples, indicating plastic deformation and local cracking associated with large strains.

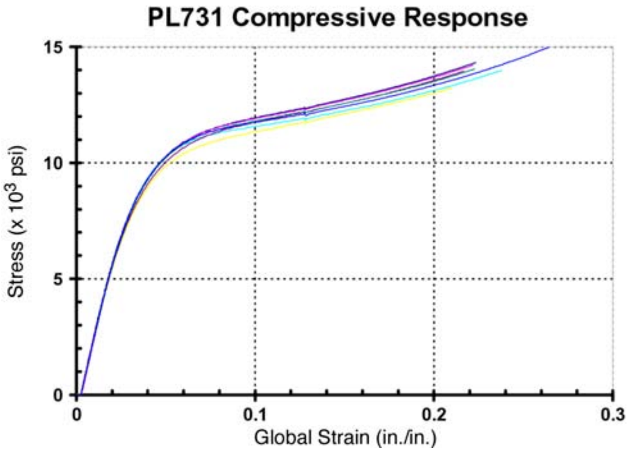

Figure 5. Combined compressive stress-strain curves for the bulk adhesive (eight samples).

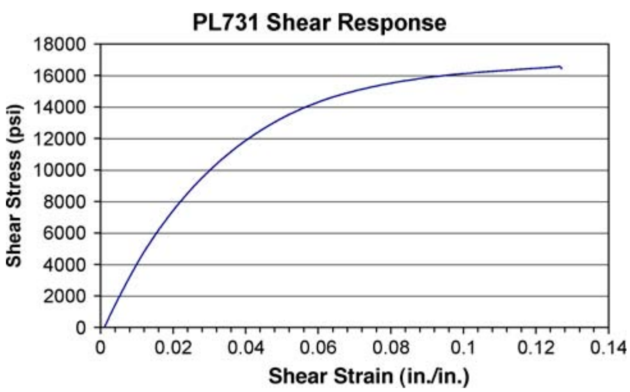

Figure 6. Shear stress-strain curve for bulk adhesive.

The hollow cylindrical specimen still did not fail before exceeding the maximum capability of the test equipment. Hence tests are being planned by the V-notched beam method to determine the shear properties of the bulk adhesive.

Preliminary quasi-static and low-speed dynamic fracture toughness tests were completed using the compact tension specimen geometry. The specimens were machined from an 8-mm-thick bulk adhesive plaque per the geometry specified in ASTM D5045. The technique developed for making near void-free 3-mm-thick plaques was also used for making these plaques. The tests were conducted on a conventional closed-loop, servo-hydraulic machine at rates of 0.02, 2.5, 25, and 1000 mm/s with three specimens tested at each rate. An untested and a tested specimen are shown in Figure 7. From these initial tests, there appeared to be an initial drop in the fracture toughness as a function of load rate, but the initial quasi-static value appeared to be much greater than

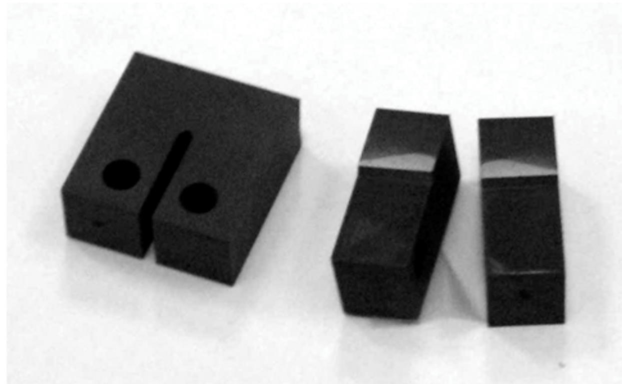

Figure 7. An untested and a tested bulk adhesive compact tension specimen.

typical values for epoxy systems. The experimental data and test methodology were evaluated for their validity, and it was determined that the target velocities were not achieved prior to load application. Consequently, the test setup was modified to include a slack adapter, and the tests were repeated at 0.02, 100, 500, and 1000 mm/s. Check-out tests were completed, and it was determined that the target velocities could be achieved prior to the load application. There was a drop in fracture toughness as loading rate was increased from 0.02 to 100 mm/s. At rates of 500 and 1000 mm/s it was difficult to discern the relatively small loads generated by the test specimen from the contributions of the momentum generated by the 10-lb slack adapter (see Figure 8). Hence, use of alternate specimen geometries like the single-edge notch bend (SENB) to determine fracture toughness at 500 and 1000 mm/s are being investigated.

Figure 8. Slack adapter.

Coupon-level joint configurations will consist of double-notch shear (DNS) and single-lap shear (SLS) test specimen geometries. Joint parameters that will be investigated are the adhesive thickness, overlap length, and fillet geometry. Moiré interferometry will be used to study the full-field deformation pattern in the bond-line during static testing of the SLS joint specimens. The crack growth characteristics of an adhesive joint will be quantified by conducting Mode I, Mode II, and Mixed Mode fracture tests using double-cantilever beam (DCB), end-notch flexure (ENF), and mixed-mode bending (MMB) specimen geometries, respectively. SLS tests were conducted at 0.02 mm/s on specimens with adhesive thickness and overlap length of 0.6 mm and 12.7 mm, respectively. Two types of adhesives were used: one that was subjected to heat treatment, and the other that was not heat treated. The SLS specimens having the adhesive not subjected to heat treatment recorded higher shear strength values (22.56 MPa) when compared to the ones that went through heat treatment (18.78 MPa). More SLS and DNS test specimens with different overlap lengths and thicknesses are currently being prepared.

Component testing in Task 3 was scheduled to commence in the last half of FY 2004 but will likely be delayed due to the issues stated above. Component testing will consist of unbonded and adhesively bonded upper rail sections. The testing will include static and dynamic crush loads, and axial and lateral impact loads. The TMAC at ORNL and test sleds will be used for the dynamic testing. The unbonded tests are to establish a baseline, and then the results from Task 2 will guide the joint design such that bonded sections will be built to either fail or not fail in the joint. Some of these tests will be repeated using scaled geometries to get an initial look at scale effects.

To determine if the baseline tube geometry would have any stability problems, that is, tube buckling would be the failure mode instead of a progressive crush, two unbonded tubes and two bonded tubes were tested at 500 mm/s and 4000 mm/s using TMAC. The tube geometry was square with nominal dimensions of 100 mm × 100 mm × 2 mm, and the length was 380 mm for the unbonded tube and 300 mm for the bonded tube. The bonded tubes were fabricated by using two c-channels having ply drop-offs to form a stepped scarf joint. The results are shown in Figures 9–12

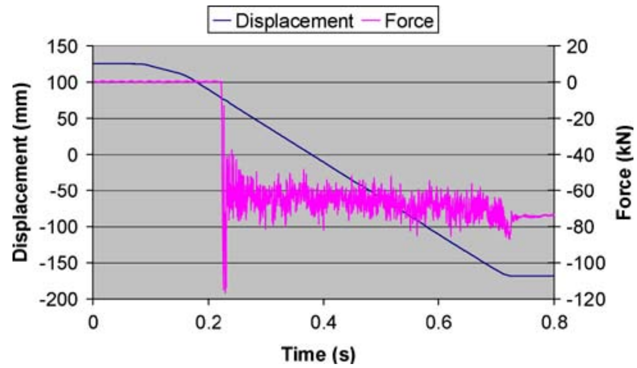

Figure 9. Unbonded tube tested at 500 mm/s.

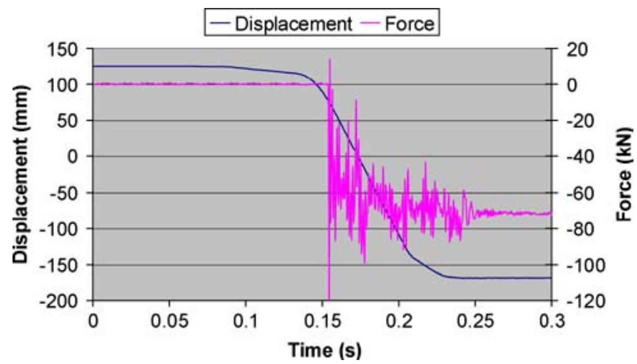

Figure 10. Unbonded tube tested at 4000 mm/s.

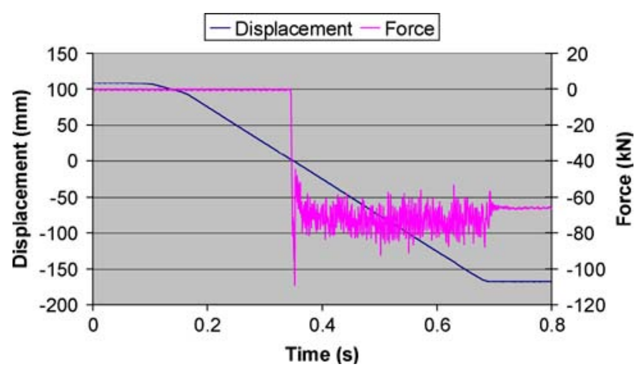

Figure 11. Bonded tube tested at 500 mm/s.

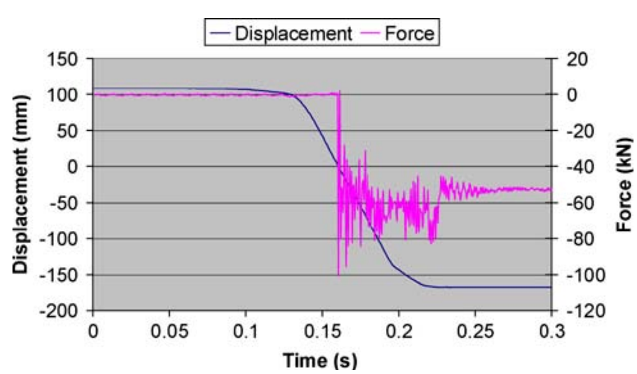

Figure 12. Bonded tube tested at 4000 mm/s.

and indicate a very well behaved progressive crush response with little difference between the bonded and unbonded tube responses. The substrate failed in a brittle fashion and literally exploded into tiny pieces (see Figure 13).

In Task 4, the computational tools development will consist of analyzing the test geometries at both the coupon level and component level, developing new material models, and developing new test methods to support the model development. This task is conducted in parallel with Tasks 2 and 3. The coupon- and component-level analyses will be completed using existing material models that are available in finite-element analysis (FEA) tools such as ABAQUS and LS-DYNA. The bond-line deformations predicted by the analyses will be compared with the Moiré experimental results. Also, the effects of bond-line thickness and length, fillet, and loading rate on the stress distribution in the joint will be correlated with the experimental results. The model development effort will consider new constitutive laws, progressive damage algorithms, new finite elements for modeling the adhesive layer, and new computationally efficient techniques. In support of this effort, new test methods will be developed for characterizing strain-rate effects and dynamic fracture.

Figure 13. Progressive crush failure of unbonded tube tested at 4000 mm/s.

Summary

Highlights of the progress during this reporting period follow:

1. Manufactured all bulk adhesive samples for tension, compression, shear, and fracture tests.
2. Completed bulk adhesive tensile and compression tests. Results indicate excellent consistency. Data have been supplied to the ACC partners for implementation in the FEA.
3. Completed preliminary shear and fracture toughness tests on bulk adhesive, and the results are being reviewed by the project team for their validity.
4. The chopped carbon fiber substrate material was replaced with a carbon fiber braided material as a result of excessive variability in the chopped fiber material data and inability to fabricate high-quality tubular specimens.
5. Machined all substrate material samples for tension, compression, and shear tests.
6. Characterized static behavior of the braided carbon fiber substrate under uniaxial tension and compression loads. Results indicate excellent consistency. Completed limited dynamic tensile tests on the braided carbon fiber substrate.
7. Completed preliminary static tests on specimens having single-lap joint geometry.
8. Completed stability testing for progressively crushing both bonded and unbonded tubes at dynamic rates.